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An Integrated Decision-Making Method Based on Neutrosophic Numbers for Investigating Factors of Coastal Erosion

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Abstract: The recent boom of various integrated decision-making methods has attracted many researchers to the field. The recent integrated Analytic Network Process and Decision Making Trial and Evaluation Laboratory (ANP–DEMATEL) methods were developed based on crisp numbers and fuzzy numbers. However, these numbers are incapable of dealing with the indeterminant and inconsistent information that exists in real-life problems. This paper proposes improvements to the integrated ANP–DEMATEL method by bringing together the neutrosophic numbers, the ANP method, and the DEMATEL method, which are later abbreviated to NS-DANP. The proposed NS-DANP method can handle the indeterminacy elements in the decision-making environment, as the single-valued neutrosophic numbers are used in the decision analysis. This proposed NS-DANP modification method includes linguistic variables representing the single-valued neutrosophic numbers (SVNNs), and also introduces the single-valued neutrosophic weighted averaging (SVNWA) aggregation operator to aggregate the decision makers' judgments instead of the typical averaging method. The applicability of the proposed method is illustrated by a case study of the coastal erosion problem along the Peninsular Malaysia coastline, where 12 factors were considered. Three experts of coastal erosion from different organizations were invited to elicit their linguistic judgments on the cause–effect of the coastal erosion. The seven-step decision approach was developed to acquire the weightage of each coastal erosion factor. The outcome of this study reveals that coastal development is the riskiest factor toward coastal erosion. The weight of factors and the cause–effect diagram could be very helpful for government and stakeholders to project a better mitigation plan for the coastal erosion problem. Comparative analysis is also provided to check the feasibility of the proposed method.

Keywords: decision making; single-valued neutrosophic set; coastal erosion management; DEMATEL; analytic network process

1. Introduction

Real-world problems involving multiple attributes and alternatives can only be solved using multi-criteria decision making (MCDM) tools. There are many well-known MCDM methods in the decision-making field; for instance, the Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), VlseKriterijumska Optimizacija I Kompromisno Resenje technique (VIKOR), Elimination and Choice Expressing Reality (ELECTRE), Grey Relational Analysis (GRA), Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE), Decision Making Trial and Evaluation Laboratory (DEMATEL), and a hybrid of MCDM methods. Every MCDM method has its own specialty and advantages for solving complicated real problems. As for clarifying the interrelationships of criteria, the DEMATEL method is the best method that has been developed for this purpose. The DEMATEL method was developed by the Science and Human Affairs Program of the Battelle Memorial Institute of Geneva, and has been well-known for its capability in dealing with the degree of importance of evaluation criteria, and more importantly to build cause–effect relationships among the evaluation criteria [1]. By pairwise comparisons of the interactions among criteria, the method utilizes matrix operations and mathematical techniques to quantify the causality and confirm the interdependence among criteria [2]. The causal diagram portrays a clear causal relationship and the degree of influence among the criteria. Recently, several studies have employed the DEMATEL method in various problems, such as those regarding cloud service selection [3], business intelligence [4], health technology assessment [5], the performance of a manufacturing company [6], supply chain [7,8], coastal erosion [9], and the auto components manufacturing sector [10].

One of the established MCDM tools for handling the feedback and dependencies among criteria and clusters is ANP [11]. The ANP method was introduced by Saaty [12] to avoid the hierarchical constraint in the analytic hierarchy process (AHP). Furthermore, the ANP method is used to determine the composite weights of the criteria through the development of a 'supermatrix' [13]. The supermatrix is actually a partitioned matrix that represents a relationship between two clusters in a system [14]. In addition to this, along the process of obtaining the final weights, arrays of elements in a matrix are used to easily convey the mechanisms of the methodology and show how dependencies function [15]. Therefore, the supermatrix is the better option, especially when involving a greater number of elements. However, there are a few flaws in the standalone ANP method. One of them is the assumption that each cluster has the same weight. This assumption is not sensible, since the weight of each cluster has a high possibility of being different from each other. Another shortcoming of ANP is that the assessment survey involves too many pairwise comparisons. This may lead to inconsistent judgment, which is time consuming and difficult to interpret. Therefore, the hybridization of DEMATEL and ANP methods has been widely explored, and has been recognized for supporting the imperfections in the solely ANP method.

Besides the combination of the DEMATEL–ANP methods, there are several integrations that promote DEMATEL that have been explored, such as the hybrid of AHP and DEMATEL [16], DEMATEL and TOPSIS [17], grey-based DEMATEL [18], DEMATEL and adaptive neuro-fuzzy inference systems (ANFIS) [6], DEMATEL and fuzzy inference system (FIS) [19], DEMATEL and VIKOR [20], DEMATEL and data envelopment analysis (DEA) [21], DEMATEL–ANP with DEA [22,23], DEMATEL, ANP, and PROMETHEE II [24], DEMATEL with ANP and the Multi-Attributive Ideal-Real Comparative Analysis (MAIRCA) method [25], DEMATEL with ANP and ELECTRE [26], DEMATEL with ANP and VIKOR [27], DEMATEL with ANP, GRA, and VIKOR [28], and DEMATEL with ANP and TOPSIS [29].

Generally, ANP studies comprise three main components, which are the network structuring of the problem, coping with inner and outer dependencies through the pairwise comparison, and forming the weighted supermatrix. According to Baykasoklu and Golcuk [30], there are four types of integrated DEMATEL–ANP technique in the literature. The first category employs DEMATEL merely for structuring the network relationship map (NRM). The inner and outer dependencies and weighted supermatrix are obtained via the traditional ANP method. The second category utilizes DEMATEL to deal with the inner dependencies. The criteria structuring, the outer dependencies, and the weighted supermatrix are accomplished using the ANP method. This category benefits from avoiding the difficulty of pairwise comparison of the ANP method. The third category adopts DEMATEL for obtaining the clusters' weights and constructing the NRM. The inner and outer dependencies are handled via the ANP method. The main purpose of this category is to incorporate the unequal weights of clusters into the formation of the supermatrix. Lastly, the fourth category uses DEMATEL in establishing the NRM, handling inner and outer dependencies and weighted supermatrix formation. This type of hybridization generalizes the previous mentioned categories and is well-known as the DANP method.

However, most of the DANP method only uses the real number in their computation methodology. Since the introduction of the fuzzy set (FS) theory by Zadeh [31], the studies related to this theory have been explored widely, and its real applications have been successfully implemented in various fields, including fuzzy DEMATEL [32,33], fuzzy ANP [34,35], and fuzzy DEMATEL–ANP [36,37]. The fuzzy DEMATEL, for instance, is superior to the traditional DEMATEL method, because it uses linguistic variables that represent fuzzy numbers in the evaluation processes instead of integer numbers from zero to four. Fuzzy numbers (FN) are well-known numbers in an uncertain environment owing to its ability to handle uncertain information. As a result, many researchers have utilized the DEMATEL method in a fuzzy environment and used triangular fuzzy numbers (TFNs) in its method development [38,39]. Despite its capability, there is one weakness when applying TFNs into the DEMATEL method, which has been pointed out by Pandey and Kumar [40]. According to Pandey and Kumar [40], the computation of a multiplicative inverse of fuzzy matrix in the DEMATEL method is invalid, because the elements in the matrix are dependent with each other, and thus the computation of the multiplicative inverse of the fuzzy matrix cannot be implemented separately. These flaws can be seen in many studies that apply the TFNs into DEMATEL methods: [32,41,42] just to cite a few. Besides TFNs, DEMATEL is applied with other sets such as trapezoidal FS [43], type-2 FS [44], interval type-2 FN [16,45], intuitionistic fuzzy sets (IFS) [46–48], interval rough sets [25], hesitant fuzzy linguistic term sets [49], and an interval-valued hesitant fuzzy set [50].

Besides that, the traditional FN only expresses one single value of membership function, $\mu_A(x) \in [0,1]$ of fuzzy set A. However, in most of the real applications such as an expert system, information fusion, and a belief system, we should not only consider truth-membership, but also falsity-membership [51]. Therefore, Atanassov [52] introduced intuitionistic fuzzy sets (IFSs), which extend the concept of FS by adding the degree of non-membership. Since its introduction, IFS has received significant interest among scholars, and lots of remarkable studies have been executed on developing theories of IFSs. Later, Atanassov and Gargov [53] introduced interval-valued IFS (IVIFS), which uses interval values to represent the degrees of membership and non-membership, instead of just real numbers. However, FSs, IFSs, and IVIFSs are incapable of dealing with all the types of uncertainty that exist in different real-life problems, especially when it involves indeterminant and inconsistent information. In IFSs, the indeterminacy degree, or the so-called hesitancy degree in IFS literature can be obtained by default, which is $1 - \mu_A(x) - \nu_A(x)$.

When we asked a decision maker (DM) about his or her opinion on a certain statement, he or she may evaluate the statement with three possibilities. First, he or she may state that the truthness of that statement is 0.5. Second, he or she may elicit that the degree of falsity is 0.6, and third, that the degree of unsure is 0.2, which is beyond the scope of FSs, IFSs, and IVIFSs [51]. In a neutrosophic set (NS), indeterminacy is quantified explicitly, which means that the truth, falsity, and indeterminacy components are completely independent. NS is a set that was introduced by Smarandache [54] where each element has the degree of truth, falsity, and indeterminacy, and it is within the non-standard unit interval of $]0^-, 1^+[$. This set is clearly an extension from the standard unit interval of IFS, $[0,1]$. However, the non-standard unit of NSs are difficult to be applied in the real-case situations; therefore, Wang et al. [51] presented the notion of single-valued neutrosophic set (SVNS), which is a special case of NSs. Since its introduction, the SVNS has attracted many scholars to theoretically improve the set by introducing new concepts of measures, defining operations, aggregation operators, and correlation coefficients associated to the set [55–58]. It also has been successfully applied in various MCDM problems such as in logistics center location selection [59], teacher selection problem [60], medical diagnosis [61], etc.

The successful applications of neutrosophic numbers, especially SVNSs in the MCDM-related problems, motivated us to explore the possibility of the development of an integrated neutrosophic DEMATEL-based ANP (NS-DANP). The acronym NS-DANP will be used throughout this paper. The introduction of SVNSs in the DEMATEL method would enhance the efficiency in handling the uncertainty and indeterminacy information that exists during the pairwise comparison evaluation process. In addition, to the best of our knowledge, there are no studies in the previous literature that used neutrosophic sets in an integrated DEMATEL and ANP method. In contrast to the other ANP–DEMATEL methods, this proposed NS-DANP method makes the computation a lot easier, as it generalizes the other hybrid ANP–DEMATEL methods. In addition, comparative analysis is carried out to show the applicability and effectiveness of the proposed NS-DANP method under a single valued neutrosophic environment compared to other existing methods. It is consistent with most of the past research in decision analysis, where comparative analysis was made to compare their proposed methods with existing methods [62–64].

This paper has twofold purposes. First, we aim to introduce the SVNSs into the DEMATEL method, as they are superior to traditional FSs, and avoid the multiplicative inverse problem in the fuzzy DEMATEL method. Secondly, to test the applicability of the proposed method, it is applied to a case study of coastal erosion problem along the Peninsular Malaysia coastal area. The rest of the paper is as follows. The second section discusses the preliminaries. The third section explains the proposed integrated neutrosophic DEMATEL-based ANP method (NS-DANP). Then, we provide a case study where the coastal erosion problem is implemented using the proposed methodology. The next section is continued with the comparative analysis. The last section concludes.

2. Preliminaries

This section provides some basic definitions of NSs, SVNSs, the weights of decision makers (DMs), the deneutrosophication of single-valued neutrosophic numbers, and the single-valued neutrosophic weighted averaging (SVNWA) aggregation operator.

Definition 1 ([54])**.** *Let X be a space of points, with generic elements in X denoted by x. A neutrosophic set Q in X is denoted by $Q = \{\langle x, T_Q(x), I_Q(x), F_Q(x)\rangle | x \in X\}$ where $T_Q(x)$ is the truth-membership function, $I_Q(x)$ is the indeterminacy-membership function, and $F_Q(x)$ is the falsity-membership function. The functions $T_Q(x), I_Q(x)$ and $F_Q(x)$ are real standard subsets of $]0^-, 1^+[$. That is, $T_Q(x), I_Q(x), F_Q(x) \to]0^-, 1^+[$. Thus, the sum of $T_Q(x), I_Q(x)$ and $F_Q(x)$ is $0^- \leq \sup T_Q(x) + \sup I_Q(x) + \sup F_Q(x) \leq 3^+$.*

Obviously, the non-standard subsets are difficult to be applied in real scientific and engineering areas. Hence, Wang et al. [51] presented the SVNS and defined it as follows.

Definition 2. *Let X be a space of points (objects) with generic elements in X denoted by x. An SVNS Q can be denoted by $Q = \{\langle x, T_Q(x), I_Q(x), F_Q(x)\rangle | x \in X\}$ where $T_Q(x)$ is the truth-membership function, $I_Q(x)$ is the indeterminacy-membership function, and $F_Q(x)$ is the falsity-membership function. That is, $T_Q(x), I_Q(x), F_Q(x) \to [0, 1]$ for each point x in X, and the sum of $T_Q(x), I_Q(x)$ and $F_Q(x)$ satisfies the condition $0 \leq T_Q(x) + I_Q(x) + F_Q(x) \leq 3$.*

The weight of DMs may be distinct from each other. The DM's weights can be obtained by the following definition [65].

Definition 3. *Let $Q_m = \langle T_m, I_m, F_m\rangle$* be an SVNS defined for the rating of the m-th DM. Then, the weight of the m-th DM can be written as:

$$\omega_m = \frac{1 - \sqrt{\left\{(1 - T_m)^2 + (I_m)^2 + (F_m)^2\right\}/3}}{\sum_{m=1}^{p}\left(1 - \sqrt{\left\{(1 - T_m)^2 + (I_m)^2 + (F_m)^2\right\}/3}\right)} \tag{1}$$

Further, in any decision analysis, the consensus decision making is the important key in achieving a promising solution. In this regard, the formation of an aggregated decision matrix is a must where all the individual DMs' judgments are aggregated. By incorporating the weights of DMs in Definition

3, the aggregated SVNS decision matrix can be computed using the SVNWA aggregation operator defined in Definition 4 [66].

Definition 4. *Let* $A^{(m)} = \left(a_{ij}^{(m)}\right)_{n \times n}$ *be the individual SVNS decision matrix of the m-th DM and* $\omega = (\omega_1, \omega_2, \ldots, \omega_p)^T$ *be the weight vector of DM such that each* $\omega_m \in [0,1]$. $A = (a_{ij})_{n \times n}$, where

$$\begin{aligned} a_{ij} &= SVNWA_{\omega}\left(a_{ij}^{(1)}, a_{ij}^{(2)}, \ldots, a_{ij}^{(p)}\right) \\ &= \omega_1 a_{ij}^{(1)} \oplus \omega_2 a_{ij}^{(2)} \oplus \ldots \oplus \omega_p a_{ij}^{(p)} \\ &= \left\langle 1 - \prod_{m=1}^{p}\left(1 - T_{ij}^{(m)}\right)^{\omega_m}, \prod_{m=1}^{p}\left(I_{ij}^{(m)}\right)^{\omega_m}, \prod_{m=1}^{p}\left(F_{ij}^{(m)}\right)^{\omega_m} \right\rangle \end{aligned} \tag{2}$$

Deneutrosophication is the process of obtaining one single real number from any of the neutrosophic numbers. The deneutrosophication of SVNNs is defined as below [65].

Definition 5. *Let* $Q = \{ \langle x, T_Q(x), I_Q(x), F_Q(x) \rangle | x \in X \}$ *be an SVNN, then the deneutrosophication of Q is the process of set Q mapping into a real number* $\chi \in X$ *i.e.,* $f : Q \rightarrow \chi$ *for* $x \in X$. *The set Q is reduced to a crisp number* $\chi \in X$. Therefore, the deneutrosophication can be computed as Equation (3).

$$\chi_Q = 1 - \sqrt{\left\{ (1 - T_Q(x))^2 + (I_Q(x))^2 + (F_Q(x))^2 \right\} / 3} \tag{3}$$

3. Proposed Method

The DANP hybrid technique with SVNSs (NS-DANP) is adopted in this study. The NS-DANP approach does not only apply neutrosophic DEMATEL to obtain the NRM and the degree of influences of dimensions and criteria. Instead, the NS-DANP that is incorporated normalizes the total-influence matrix T of DEMATEL into an unweighted supermatrix of ANP. In addition, the relationships element reflected from the total-influence matrix of DEMATEL is similar to the idea of ANP, which supports the importance of criteria through questionnaires. Besides that, this proposed NS-DANP method is better than the integrated DEMATEL and AHP, because the AHP only considers the unidirectional interactions between components in the lower level of the hierarchy with respect to the components in upper level of the hierarchy, while the ANP method can handle the interactions among inner dependency, outer dependency, and self-feedback [30]. Therefore, the ANP is a practical tool to solve the real complex problem by integrating the key interrelationships of criteria in the form of the supermatrix. The supermatrix or influence matrix is a generalization of the AHP, since the ANP offers more flexible interactions among clusters and criteria. Development of the proposed NS-DANP method is carried out in three phases. The initial phase is where the collection of data is executed via the linguistic evaluation of DMs. The second phase analyzes the data using the developed neutrosophic DEMATEL method. The total-influence matrix of DEMATEL is incorporated into the ANP methodology in Phase 3 to get the influential weights of criteria. To highlight the new developed structure of the proposed NS-DANP method, the three phases are visualized as in Figure 1.

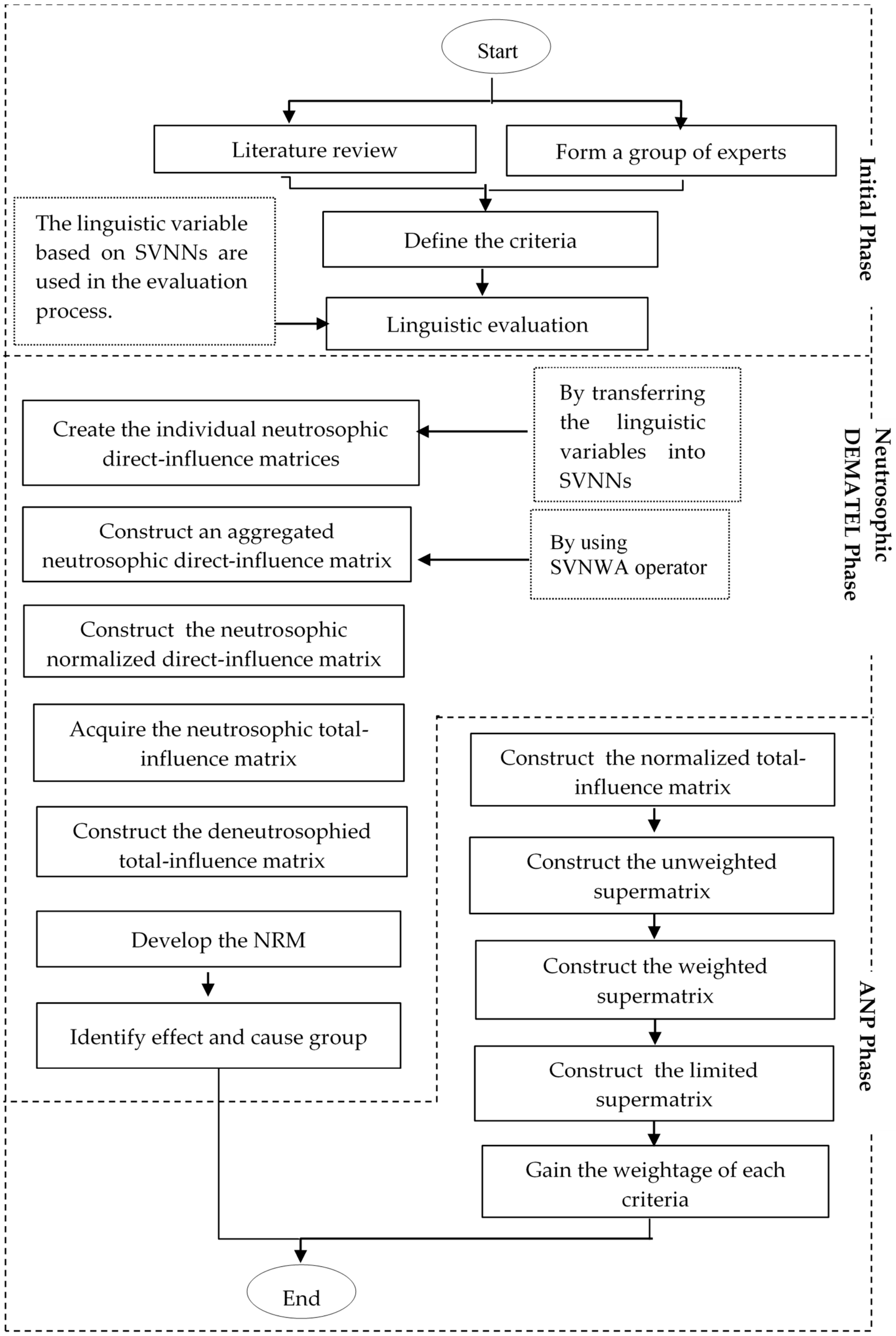

Figure 1. The framework of the proposed neutrosophic Decision Making Trial and Evaluation Laboratory (DEMATEL)-based Analytic Hierarchy Process (ANP) (NS-DANP) method.

In the first phase, the questionnaire is developed, a group of experts is recognized, the dimensions and influencing criteria are finalized, and the linguistic variables are set to carry out the pairwise comparison evaluation and get the information for this study. After obtaining the data, the linguistic variable information is transformed into SVNSs in matrix form. The individual experts' initial direct-influence matrices are aggregated using the SVNWA aggregation operator. This aggregation operator is introduced into this study, as it is easy to compute and efficient in aggregating SVNSs. Then, in the second phase, the DEMATEL method based on SVNS is implemented to develop the NRM and classify the influencing criteria into cause and effect groups. The third phase is where the integration between DEMATEL and ANP commences. The total-influence matrix obtained from the DEMATEL method is utilized in the ANP method. As a result of this NS-DANP integration, the weights of each influencing criteria are obtained. The individual steps of the proposed NS-DANP method are shown below.

Step 1. Establish the neutrosophic aggregated direct-influence matrix A^G.

In this step, each expert was asked to state the degree of direct influence based on the scale ranging from zero to four, which indicates the linguistic variable from "no influence" to "very high influence". The linguistic variable is used in most of the MCDM evaluation process, because of the human language that is easy to be interpreted for gaining information from experts' purposes. Table 1 shows the zero to four scale, the linguistic variables, and their corresponding SVNSs adopted from Biswas et al. [65].

Table 1. Linguistic variable and its corresponding single-valued neutrosophic numbers (SVNNs) [65].

Integer	Linguistic Variable	SVNNs
0	Very unimportant (VU)	$\langle 0.1, 0.8, 0.9 \rangle$
1	Unimportant (U)	$\langle 0.35, 0.6, 0.7 \rangle$
2	Medium important (M)	$\langle 0.5, 0.4, 0.45 \rangle$
3	Important (I)	$\langle 0.8, 0.2, 0.15 \rangle$
4	Absolutely important (AI)	$\langle 0.9, 0.1, 0.1 \rangle$

The evaluation information obtained from each expert will be converted into the neutrosophic direct-influence matrix form. Since each expert produces an individual neutrosophic direct-relation matrix, a neutrosophic aggregated direct-relation matrix needs to be derived by the SVNWA aggregation operator using Equation (2). The weights of experts need to be calculated beforehand using Equation (1).

Hence, the neutrosophic aggregated direct-influence matrix, A^G, is denoted as below.

$$A^G = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix},$$

where a_{ij} is SVNSs with the form of $\langle T_{ij}, I_{ij}, F_{ij} \rangle$, and indicates the influence degree of factor i on factor j.

Step 2. Construct the neutrosophic normalized direct-influence matrix, B.

The neutrosophic normalized direct-influence matrix can be obtained through Equations (4) and (5).

$$B = k \times A^G, \tag{4}$$

$$\text{where } k = \min\left[\frac{1}{\max\limits_i \sum_{j=1}^{n} T_{ij}}, \frac{1}{\max\limits_j \sum_{i=1}^{n} T_{ij}}\right] \tag{5}$$

Step 3. Acquire the total direct-influence matrix, S.

For this step, the multiplicative inverse of $(I - B)$ matrices need to be calculated in order to get the total direct-influence matrices. In this regard, Pandey and Kumar [40] cautioned in their commenting paper that it was an invalid step for the computation of the multiplicative inverse of fuzzy matrices. This invalid inverse operation has been noticed in most of the previous articles when applying the fuzzy DEMATEL method [32,41,42]. In the fuzzy DEMATEL method, the multiplicative inverse of fuzzy matrices was done separately by its elements. This is invalid, since the elements of fuzzy numbers are dependent on each other. In this regard, this paper utilizes the neutrosophic numbers so as to divert the flaws that exist in the fuzzy DEMATEL method. Since the elements in neutrosophic sets are independent from each other, the multiplicative inverse of neutrosophic matrices can be done separately. The introduction of neutrosophic sets in DEMATEL is seen as the way to overcome the drawback in fuzzy DEMATEL methodology.

The matrix S can be obtained by the following equations:

$$\begin{aligned} S &= B + B^2 + \ldots + B^k \\ &= B\left(1 + B + B^2 + \ldots + B^{k-1}\right)(1 - B)(1 - B)^{-1} \\ &= B\left(1 - B^k\right)(1 - B)^{-1} \\ &= B(1 - B)^{-1} \text{when} \lim_{k \to \infty} B^k = [0]_{n \times n} \end{aligned} \tag{6}$$

where $S = \left[s_{ij}\right]_{n \times n} = \begin{bmatrix} s_{11} & \cdots & s_{1n} \\ \vdots & \ddots & \vdots \\ s_{n1} & \cdots & s_{nn} \end{bmatrix}$, and $s_{ij} = \left\langle T_{ij}(x), I_{ij}(x), F_{ij}(x) \right\rangle$, then

$$\text{Matrix } \left[T_{ij}\right] = B_T(I - B_T)^{-1} \tag{7}$$

$$\text{Matrix } \left[I_{ij}\right] = B_I(I - B_I)^{-1} \tag{8}$$

$$\text{Matrix } \left[F_{ij}\right] = B_F(I - B_F)^{-1} \tag{9}$$

where I is the neutrosophic identity matrix with diagonal elements of $\langle 1, 1, 1 \rangle$ and non-diagonal elements of $\langle 0, 0, 0 \rangle$.

Then, the elements in matrix S is deneutrosophied to obtain crisp numbers. The deneutrosophication can be computed as Equation (3). From the deneutrosophied matrix S, the prominence and relation of each criterion can be derived by Equations (10) and (11):

$$a = (a_i)_{n \times 1} = \left[\sum_{j=1}^{n} s_{ij}\right]_{n \times 1} \tag{10}$$

$$b = (b_j)_{1 \times n} = \left[\sum_{i=1}^{n} s_{ij}\right]_{1 \times n} \tag{11}$$

where a_i is the sum of rows of matrix S, and b_j is the sum of columns of matrix S. The $(a_i + b_i)$ values indicate the importance of each criterion. The $(a_i - b_i)$ values can be categorized into two groups, which are the net receiver and net causer. The positive $(a_i - b_i)$ values indicate the criterion i affecting the other criterion, while if the $(a_i - b_i)$ value is negative, the criterion i is being influenced by the other criteria.

Step 4. Draw the network relationship map (NRM).

The NRM can be drawn by mapping $(a_i + b_i, a_i - b_i)$, which provides an understandable structure that clearly expresses the relationship among criteria, degree of influences, and impacts of each criterion. The threshold value is set to eliminate the small influences in matrix S. The threshold value is given by an expert based on their opinions. After verifying the interrelationship among dimensions and criteria by neutrosophic DEMATEL, the ANP method is incorporated to determine the influential weights of each criteria.

Step 5. Form the unweighted supermatrix.

The neutrosophic total-influence matrix for criteria obtained from the neutrosophic DEMATEL method is denoted by S_c.

$$S_c = \begin{array}{cc} & \\ D_1 & \begin{array}{c} c_{11} \\ c_{12} \\ \vdots \\ c_{1m_1} \end{array} \\ D_2 & \begin{array}{c} c_{21} \\ c_{22} \\ \vdots \\ c_{2m_2} \end{array} \\ \vdots & \vdots \\ D_n & \begin{array}{c} c_{n1} \\ c_{n2} \\ \vdots \\ c_{nm_n} \end{array} \end{array} \overset{\begin{array}{cccc} D_1 & D_2 & \cdots & D_n \\ c_{n1} \ldots c_{nm_n} & c_{n1} \ldots c_{nm_n} & \cdots & c_{n1} \ldots c_{nm_n} \end{array}}{\begin{bmatrix} S_c^{11} & S_c^{12} & \cdots & S_c^{1n} \\ S_c^{21} & S_c^{22} & \cdots & S_c^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ S_c^{n1} & S_c^{n2} & \cdots & S_c^{nn} \end{bmatrix}} \quad (12)$$

To obtain matrix s_c^α, the matrix S_c needs to be normalized by dimensions as shown in Equation (13):

$$S_c^\alpha = \begin{array}{cc} & \\ D_1 & \begin{array}{c} c_{11} \\ c_{12} \\ \vdots \\ c_{1m_1} \end{array} \\ D_2 & \begin{array}{c} c_{21} \\ c_{22} \\ \vdots \\ c_{2m_2} \end{array} \\ \vdots & \vdots \\ D_n & \begin{array}{c} c_{n1} \\ c_{n2} \\ \vdots \\ c_{nm_n} \end{array} \end{array} \overset{\begin{array}{cccc} D_1 & D_2 & \cdots & D_n \\ c_{n1} \ldots c_{nm_n} & c_{n1} \ldots c_{nm_n} & \cdots & c_{n1} \ldots c_{nm_n} \end{array}}{\begin{bmatrix} S_c^{\alpha 11} & S_c^{\alpha 12} & \cdots & S_c^{\alpha 1n} \\ S_c^{\alpha 21} & S_c^{\alpha 22} & \cdots & S_c^{\alpha 2n} \\ \vdots & \vdots & \ddots & \vdots \\ S_c^{\alpha n1} & S_c^{\alpha n2} & \cdots & S_c^{\alpha nn} \end{bmatrix}} \quad (13)$$

where $S_c^{\alpha 11}$ can be computed by Equations (14) and (15), and $S_c^{\alpha nn}$ is computed the same way.

$$d_{ci}^{11} = \sum_{j=1}^{m_1} s_{ij}^{11},\ i = 1, 2, \ldots, m_1 \tag{14}$$

$$S_c^{\alpha 11} = \begin{bmatrix} s_{c11}^{11}/d_{c1}^{11} & \cdots & s_{c1j}^{11}/d_{c1j}^{11} & \cdots & s_{c11}^{11}/d_{c1}^{11} \\ \vdots & & \vdots & & \vdots \\ s_{ci1}^{11}/d_{ci}^{11} & \cdots & s_{cij}^{11}/d_{ci}^{11} & \cdots & s_{cim_1}^{11}/d_{ci}^{11} \\ \vdots & & \vdots & & \vdots \\ s_{cm_11}^{11}/d_{cm_1}^{11} & \cdots & s_{cm_1j}^{11}/d_{cm_1}^{11} & \cdots & s_{cm_1m_1}^{11}/d_{cm_1}^{11} \end{bmatrix} = \begin{bmatrix} s_{c11}^{\alpha 11} & \cdots & s_{c1j}^{\alpha 11} & \cdots & s_{c1j}^{\alpha 11} \\ \vdots & & \vdots & & \vdots \\ s_{ci1}^{\alpha 11} & \cdots & s_{cij}^{\alpha 11} & \cdots & s_{cim_1}^{\alpha 11} \\ \vdots & & \vdots & & \vdots \\ s_{cm_11}^{\alpha 11} & \cdots & s_{cm_1j}^{\alpha 11} & \cdots & s_{cm_1m_1}^{\alpha 11} \end{bmatrix} \tag{15}$$

To acquire the unweighted supermatrix ψ, the interdependence relationship among dimensions is incorporated. It is based on transposition of a neutrosophic total-influence matrix of criteria $\psi = (S_c^{\alpha})'$.

$$\psi = \begin{array}{cc} & \begin{array}{cccc} D_1 & D_2 & \cdots & D_n \\ c_{n1} \ldots c_{nm_n} & c_{n1} \ldots c_{nm_n} & \cdots & c_{n1} \ldots c_{nm_n} \end{array} \\ \begin{array}{cc} D_1 & \begin{array}{c} c_{11} \\ c_{12} \\ \vdots \\ c_{1m_1} \end{array} \\ D_2 & \begin{array}{c} c_{21} \\ c_{22} \\ \vdots \\ c_{2m_2} \end{array} \\ \vdots & \vdots \\ D_n & \begin{array}{c} c_{n1} \\ c_{n2} \\ \vdots \\ c_{nm_n} \end{array} \end{array} & \begin{bmatrix} \psi^{11} & \psi^{12} & \cdots & \psi^{1n} \\ \psi^{21} & \psi^{22} & \cdots & \psi^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \psi^{n1} & \psi^{n2} & \cdots & \psi^{nn} \end{bmatrix} \end{array} \tag{16}$$

where the matrix ψ^{11} represents the vector of factors in the D_1 group to the factors in the D_1 group as well. If the matrix ψ^{11} is zero, it indicates that the factors of that group are independent. In the similar way, the matrix ψ^{12} until ψ^{nn} can be obtained.

$$\psi^{11} = \begin{array}{c} \\ c_{11} \\ \vdots \\ c_{12} \\ \vdots \\ c_{1m_1} \end{array} \begin{array}{c} \begin{array}{ccccc} c_{11} & & c_{12} & & c_{1m_1} \end{array} \\ \begin{bmatrix} s_{c11}^{\alpha 11} & \cdots & s_{ci1}^{\alpha 11} & \cdots & s_{cm_11}^{\alpha 11} \\ \vdots & & \vdots & & \vdots \\ s_{c1j}^{\alpha 11} & \cdots & s_{cij}^{\alpha 11} & \cdots & s_{cm_11j}^{\alpha 11} \\ \vdots & & \vdots & & \vdots \\ s_{c1m_1}^{\alpha 11} & \cdots & s_{cim_1}^{\alpha 11} & \cdots & s_{cm_1m_1}^{\alpha 11} \end{bmatrix} \end{array} \tag{17}$$

Step 6. Construct the weighted supermatrix.

In order to determine the weighted supermatrix, normalize the sum of each column in the dimensions of the total direct-influence matrix, as shown in Equation (18).

$$S_D = \begin{bmatrix} s_D^{11} & \cdots & s_D^{1j} & \cdots & s_D^{1n} \\ \vdots & & & & \\ s_D^{i1} & \cdots & s_D^{ij} & \cdots & s_D^{in} \\ \vdots & & \vdots & & \vdots \\ s_D^{n1} & \cdots & s_D^{nj} & \cdots & s_D^{nn} \end{bmatrix} \tag{18}$$

Normalizing matrix S_D yields the new matrix S_D^α, as shown in Equation (19):

$$S_D^\alpha = \begin{bmatrix} s_D^{11}/d_1 & \cdots & s_D^{1j}/d_1 & \cdots & s_D^{1n}/d_1 \\ \vdots & & & & \\ s_D^{i1}/d_2 & \cdots & s_D^{ij}/d_2 & \cdots & s_D^{in}/d_2 \\ \vdots & & \vdots & & \vdots \\ s_D^{n1}/d_3 & \cdots & s_D^{nj}/d_3 & \cdots & s_D^{nn}/d_3 \end{bmatrix}$$

$$= \begin{bmatrix} s_D^{\alpha 11} & \cdots & s_D^{\alpha 1j} & \cdots & s_D^{\alpha 1n} \\ \vdots & & & & \\ s_D^{\alpha i1} & \cdots & s_D^{\alpha ij} & \cdots & s_D^{i\alpha n} \\ \vdots & & \vdots & & \vdots \\ s_D^{\alpha n1} & \cdots & s_D^{\alpha nj} & \cdots & s_D^{\alpha nn} \end{bmatrix} \tag{19}$$

Let the normalized total-influence matrix T_D^α be filled into the unweighted supermatrix to obtain a weighted supermatrix, as shown in Equation (20):

$$\psi^\alpha = \begin{bmatrix} s_D^{\alpha 11} \times \psi^{11} & s_D^{\alpha 12} \times \psi^{12} & \cdots & \cdots & s_D^{\alpha n1} \times \psi^{1n} \\ s_D^{\alpha 12} \times \psi^{12} & s_D^{\alpha 22} \times \psi^{22} & \vdots & & \vdots \\ \vdots & \cdots & s_D^{\alpha ij} \times \psi^{ij} & \cdots & s_D^{\alpha ni} \times \psi^{ni} \\ \vdots & & \vdots & & \vdots \\ s_D^{\alpha n1} \times \psi^{n1} & s_D^{\alpha 2n} \times \psi^{2n} & \cdots & \cdots & s_D^{\alpha nn} \times \psi^{nn} \end{bmatrix} \tag{20}$$

Step 7. Construct the limited supermatrix.

The limited supermatrix can be obtained by raising the weighted supermatrix to a sufficiently large power k, until the supermatrix converged and become a long-term stable supermatrix to get the global weights, such that $\lim_{k\to\infty}(\psi^\alpha)^k$. The influential weights need to be deneutrosophied using Equation (3) to get the crisp final influential weights.

4. Case Study

In this section, a case study is presented to verify the developed NS-DANP method in finding the interrelationship between factors and the influential weights of factors of coastal erosion. In this section, the word 'factor' is used rather than criteria, as it is widely used in the literature to address the coastal erosion problem, while the word 'dimension', which has the same meaning as clusters, is maintained.

4.1. Background of the Problem

Malaysia comprises two regions, which are the Peninsular Malaysia and Sabah-Sarawak region. Peninsular Malaysia has a 1972-km long coastline with a west coast facing the Straits of Malacca and an east coast fronting the South China Sea. The west coast of Peninsular Malaysia is a mud flats kind of beach, while the east coastline is dominated by sandy beaches. The sandy beaches are continuously enriched by sediment loads from several major rivers such as the Kelantan River, Terengganu River, and Pahang River. Unlike the mud flats' shoreline areas, the mangrove colonies are isolated to river estuaries and inlets for a sand-dominated shoreline. In this study, our focus is to study the coastal erosion problem for the sandy beaches' shoreline specifically along the east coast of Peninsular Malaysia.

4.2. Data Collection and Decision Makers

The data were collected via face-to-face interview with three professional experts in the coastal erosion problem, namely DM_1, DM_2, and DM_3. The experience of these experts in the coastal erosion problem is between five and 26 years. The evaluation process took about 30 min for each expert to give their judgments on 138 pairwise comparisons of three dimensions and 12 factors of coastal erosion problem. Table 2 shows the personal profile of all three decision makers. The decision makers were chosen based on their experience in the coastal erosion problem.

Table 2. Personal profiles of decision makers (DMs).

DM	Position	Sector	Experience
1	Coastal engineer	Private	20 years
2	Lecturer	Government	5 years
3	Coastal engineer	Private	26 years

4.3. Dimensions and Factors

The finalized factors of coastal erosion are revised from Luo et al. [67] along with the experts' agreement. There are three dimensions and 12 factors of coastal erosion to be considered in this study, as shown in Table 3.

Table 3. The dimensions and factors of coastal erosion.

Dimensions	Factors
Natural factors (D_1)	Wave and current (c_1)
	Sediment transport (c_2)
	Storm surge (c_3)
	Tidal range (c_4)
	Global warming (c_5)
	Beach profile and stability (c_6)
	Sea level rise (c_7)
Man-made factors (D_2)	Sand mining activities (c_8)
	Coastal development (c_9)
Socio-economic factors (D_3)	Coastal protection (c_{10})
	Budgetary revenue (c_{11})
	Coastal zone management (c_{12})

4.4. The Analysis of Data Using the Proposed NS-DANP Method

The DMs were asked to give their judgments on the influence of one dimension/factor toward another dimension/factor using pairwise comparison. The collected linguistic data were transformed into SVNS matrices using the defined linguistic variable (see Table 1). The following matrices and matrices are the individual direct-influence matrices of dimensions and factors, respectively.

$$A_D^3 = \begin{pmatrix} VU & U & I \\ I & VU & I \\ M & I & VU \end{pmatrix}$$

$$A_D^2 = \begin{pmatrix} VU & AI & I \\ I & VU & I \\ I & AI & VU \end{pmatrix}, A_D^1 = \begin{pmatrix} VU & M & AI \\ I & VU & AI \\ AI & AI & VU \end{pmatrix},$$

$$A_c^1 = \begin{pmatrix} VU & AI & I & VU & U & AI & M & M & U & AI & AI & AI \\ U & VU & U & VU & I & AI & I & U & AI & AI & AI & AI \\ I & I & VU & VU & I & I & I & I & AI & AI & I & AI \\ U & I & AI & VU & M & AI & I & I & AI & I & AI & I \\ I & AI & AI & AI & VU & I & AI & I & AI & AI & AI & AI \\ M & AI & M & M & I & VU & U & AI & I & AI & I & I \\ AI & I & AI & M & AI & AI & VU & I & AI & AI & AI & AI \\ U & AI & I & U & I & AI & M & VU & AI & I & AI & AI \\ AI & AI & AI & U & M & AI & AI & I & VU & AI & AI & AI \\ AI & AI & M & M & M & AI & AI & M & I & VU & AI & M \\ I & AI & M & U & M & M & AI & I & AI & AI & VU & AI \\ M & AI & U & VU & U & I & I & AI & AI & AI & AI & VU \end{pmatrix}$$

$$A_c^2 = \begin{pmatrix} VU & I & M & I & M & AI & U & VU & U & U & M & U \\ M & VU & VU & VU & VU & I & VU & VU & U & M & I & M \\ I & I & VU & I & VU & AI & U & VU & I & I & I & I \\ I & M & AI & VU & U & AI & I & U & I & I & M & I \\ AI & U & I & I & VU & I & AI & U & I & U & M & M \\ I & M & U & M & VU & VU & M & VU & I & I & I & M \\ M & U & M & I & VU & M & VU & U & I & I & M & I \\ M & M & U & M & M & I & I & VU & U & M & I & I \\ I & I & VU & U & U & U & U & M & VU & M & U & M \\ U & I & VU & U & U & M & U & VU & VU & VU & M & M \\ M & M & U & M & U & I & U & U & M & M & VU & I \\ U & I & VU & VU & U & U & VU & U & M & AI & I & VU \end{pmatrix}$$

$$A_c^3 = \begin{pmatrix} VU & I & M & I & U & I & I & M & I & I & I & I \\ I & VU & M & I & M & I & I & I & I & I & I & I \\ I & I & VU & I & M & I & I & M & M & I & M & I \\ I & I & I & VU & U & I & I & I & U & I & I & I \\ I & I & AI & I & VU & I & AI & M & I & I & I & I \\ I & I & M & I & U & VU & I & I & I & I & I & I \\ I & I & I & I & I & I & VU & I & I & I & I & I \\ I & AI & I & I & I & I & I & VU & I & I & I & M \\ I & AI & I & I & I & I & I & I & VU & I & I & M \\ I & I & M & I & I & I & I & M & I & VU & I & U \\ U & U & U & VU & U & U & U & I & I & I & VU & I \\ U & U & VU & U & U & U & U & I & I & I & I & VU \end{pmatrix}$$

The weights of each DM are calculated using Equation (1). Based on the experience in handling coastal erosion problems, we rate each DM as follows:

$$\{DM_1, DM_2, DM_3\} = \{I, M, I\} = \{\langle 0.8, 0.2, 0.15\rangle, \langle 0.5, 0.4, 0.45\rangle, \langle 0.8, 0.2, 0.15\rangle\}$$

From Equation (1):

$$\omega_m = \frac{1 - \sqrt{\left\{(1 - T_m)^2 + (I_m)^2 + (F_m)^2\right\}/3}}{\sum_{m=1}^{p}\left(1 - \sqrt{\left\{(1 - T_m)^2 + (I_m)^2 + (F_m)^2\right\}/3}\right)}$$

Then:

$$\omega_1 = \frac{1-\sqrt{\left\{(1-0.8)^2+(0.2)^2+(0.15)^2\right\}/3}}{\left(1-\sqrt{\left\{(1-0.8)^2+(0.2)^2+(0.15)^2\right\}/3}\right)+\left(1-\sqrt{\left\{(1-0.5)^2+(0.4)^2+(0.45)^2\right\}/3}\right)+\left(1-\sqrt{\left\{(1-0.8)^2+(0.2)^2+(0.15)^2\right\}/3}\right)}$$

Hence, we obtained the weights of each DM as:

$$\{\omega_1, \omega_2, \omega_3\} = \{0.3742, 0.2516, 0.3742\}$$

The aggregated neutrosophic direct-influence matrix A_c^G can be obtained by aggregating the individual neutrosophic direct-influence matrices A_c^1, A_c^2 and A_c^3 using Equation (2). The aggregated neutrosophic direct-influence matrix for factors A_c^G is shown in Table 4. By applying Equation (4) and Equation (5), the neutrosophic normalized direct-influence matrix, B is obtained (see Table 5). Table 6 shows the neutrosophic total-influence matrix calculated using Equations (6) to (9).

Table 4. Aggregated initial direct-influence matrix A_c^G for factors.

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}
c_1	⟨0.10, 0.80, 0.90⟩	⟨0.85, 0015, 0.13	⟨0.65, 0.31, 0.30⟩	⟨0.65, 0.34, 0.29⟩	⟨0.39, 0.54, 0.63⟩	⟨0.87, 0.13, 0.12⟩	⟨0.62, 0.34, 0.33⟩	⟨0.42, 0.48, 0.54⟩	⟨0.58, 0.40, 0.39⟩	⟨0.79, 0.20, 0.19⟩	⟨0.81, 0.18, 0.17⟩	⟨0.79, 0.20, 0.19⟩
c_2	⟨0.61, 0.36, 0.35⟩	⟨0.10, 0.80, 0.90⟩	⟨0.87, 0.13, 0.12⟩	⟨0.49, 0.48, 0.46⟩	⟨0.59, 0.37, 0.36⟩	⟨0.85, 0.15, 0.13⟩	⟨0.71, 0.28, 0.24⟩	⟨0.55, 0.43, 0.42⟩	⟨0.79, 0.20, 0.19⟩	⟨0.81, 0.18, 0.17⟩	⟨0.85, 0.15, 0.13⟩	⟨0.81, 0.18, 0.17⟩
c_3	⟨0.80, 0.20, 0.15⟩	⟨0.80, 0.20, 0.15⟩	⟨0.10, 0.80, 0.90⟩	⟨0.65, 0.34, 0.29⟩	⟨0.59, 0.37, 0.36⟩	⟨0.83, 0.17, 0.14⟩	⟨0.73, 0.26, 0.22⟩	⟨0.59, 0.37, 0.36⟩	⟨0.78, 0.20, 0.19⟩	⟨0.85, 0.15, 0.13⟩	⟨0.72, 0.26, 0.23⟩	⟨0.85, 0.15, 0.13⟩
c_4	⟨0.69, 0.30, 0.27⟩	⟨0.75, 0.24, 0.20⟩	⟨0.43, 0.30, 0.27⟩	⟨0.10, 0.80, 0.90⟩	⟨0.41, 0.52, 0.59⟩	⟨0.87, 0.13, 0.12⟩	⟨0.80, 0.20, 0.15⟩	⟨0.73, 0.26, 0.22⟩	⟨0.76, 0.23, 0.23⟩	⟨0.80, 0.20, 0.15⟩	⟨0.81, 0.18, 0.17⟩	⟨0.80, 0.20, 0.15⟩
c_5	⟨0.83, 0.17, 0.14⟩	⟨0.79, 0.20, 0.19⟩	⟨0.88, 0.12, 0.11⟩	⟨0.85, 0.15, 0.13⟩	⟨0.10, 0.80, 0.90⟩	⟨0.80, 0.20, 0.15⟩	⟨0.90, 0.10, 0.10⟩	⟨0.62, 0.34, 0.33⟩	⟨0.85, 0.15, 0.13⟩	⟨0.79, 0.20, 0.19⟩	⟨0.81, 0.18, 0.17⟩	⟨0.81, 0.18, 0.17⟩
c_6	⟨0.72, 0.26, 0.23⟩	⟨0.81, 0.18, 0.17⟩	⟨0.47, 0.44, 0.50⟩	⟨0.65, 0.31, 0.30⟩	⟨0.55, 0.43, 0.42⟩	⟨0.10, 0.80, 0.90⟩	⟨0.61, 0.36, 0.35⟩	⟨0.77, 0.22, 0.20⟩	⟨0.72, 0.26, 0.23⟩	⟨0.85, 0.15, 0.13⟩	⟨0.80, 0.20, 0.15⟩	⟨0.75, 0.24, 0.20⟩
c_7	⟨0.81, 0.28, 0.30⟩	⟨0.73, 0.26, 0.22⟩	⟨0.81, 0.18, 0.17⟩	⟨0.72, 0.26, 0.23⟩	⟨0.77, 0.22, 0.20⟩	⟨0.81, 0.18, 0.17⟩	⟨0.10, 0.80, 0.90⟩	⟨0.73, 0.26, 0.22⟩	⟨0.85, 0.15, 0.13⟩	⟨0.85, 0.15, 0.13⟩	⟨0.81, 0.18, 0.17⟩	⟨0.85, 0.15, 0.13⟩
c_8	⟨0.61, 0.36, 0.35⟩	⟨0.85, 0.14, 0.15⟩	⟨0.73, 0.26, 0.22⟩	⟨0.61, 0.36, 0.35⟩	⟨0.75, 0.24, 0.20⟩	⟨0.85, 0.15, 0.13⟩	⟨0.72, 0.26, 0.23⟩	⟨0.10, 0.80, 0.90⟩	⟨0.79, 0.20, 0.19⟩	⟨0.75, 0.24, 0.20⟩	⟨0.85, 0.15, 0.13⟩	⟨0.78, 0.20, 0.19⟩
c_9	⟨0.85, 0.15, 0.13⟩	⟨0.88, 0.12, 0.11⟩	⟨0.77, 0.22, 0.20⟩	⟨0.58, 0.40, 0.39⟩	⟨0.62, 0.34, 0.33⟩	⟨0.79, 0.20, 0.19⟩	⟨0.79, 0.20, 0.19⟩	⟨0.75, 0.24, 0.20⟩	⟨0.10, 0.80, 0.90⟩	⟨0.81, 0.18, 0.17⟩	⟨0.79, 0.20, 0.19⟩	⟨0.73, 0.24, 0.26⟩
c_{10}	⟨0.79, 0.20, 0.19⟩	⟨0.85, 0.15, 0.13⟩	⟨0.42, 0.48, 0.54⟩	⟨0.62, 0.34, 0.33⟩	⟨0.62, 0.34, 0.33⟩	⟨0.81, 0.18, 0.17⟩	⟨0.79, 0.20, 0.19⟩	⟨0.42, 0.48, 0.54⟩	⟨0.71, 0.28, 0.24⟩	⟨0.10, 0.80, 0.90⟩	⟨0.81, 0.18, 0.17⟩	⟨0.45, 0.47, 0.53⟩
c_{11}	⟨0.61, 0.36, 0.35⟩	⟨0.70, 0.28, 0.30⟩	⟨0.41, 0.52, 0.59⟩	⟨0.31, 0.60, 0.69⟩	⟨0.41, 0.52, 0.59⟩	⟨0.56, 0.39, 0.40⟩	⟨0.68, 0.31, 0.34⟩	⟨0.73, 0.26, 0.22⟩	⟨0.81, 0.18, 0.17⟩	⟨0.81, 0.18, 0.17⟩	⟨0.10, 0.80, 0.90⟩	⟨0.85, 0.15, 0.13⟩
c_{12}	⟨0.41, 0.52, 0.59⟩	⟨0.76, 0.23, 0.23⟩	⟨0.20, 0.72, 0.82⟩	⟨0.20, 0.72, 0.82⟩	⟨0.35, 0.60, 0.70⟩	⟨0.58, 0.40, 0.39⟩	⟨0.55, 0.43, 0.42⟩	⟨0.79, 0.20, 0.19⟩	⟨0.81, 0.18, 0.17⟩	⟨0.87, 0.13, 0.12⟩	⟨0.85, 0.15, 0.13⟩	⟨0.10, 0.80, 0.90⟩

Table 5. The normalized direct-influence matrix B_c for factors.

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}
c_1	⟨0.01, 0.09, 0.1⟩	⟨0.09, 0.02, 0.01⟩	⟨0.07, 0.03, 0.03⟩	⟨0.07, 0.04, 0.03⟩	⟨0.04, 0.06, 0.07⟩	⟨0.10, 0.01, 0.01⟩	⟨0.07, 0.04, 0.04⟩	⟨0.05, 0.05, 0.05⟩	⟨0.06, 0.04, 0.04⟩	⟨0.09, 0.02, 0.02⟩	⟨0.09, 0.02, 0.02⟩	⟨0.09, 0.02, 0.02⟩
c_2	⟨0.09, 0.02, 0.02⟩	⟨0.01, 0.09, 0.1⟩	⟨0.04, 0.06, 0.07⟩	⟨0.05, 0.05, 0.05⟩	⟨0.06, 0.04, 0.04⟩	⟨0.09, 0.02, 0.01⟩	⟨0.08, 0.03, 0.03⟩	⟨0.06, 0.05, 0.05⟩	⟨0.09, 0.02, 0.02⟩	⟨0.09, 0.02, 0.02⟩	⟨0.09, 0.02, 0.01⟩	⟨0.09, 0.02, 0.02⟩
c_3	⟨0.09, 0.04, 0.03⟩	⟨0.09, 0.02, 0.02⟩	⟨0.01, 0.09, 0.1⟩	⟨0.07, 0.04, 0.03⟩	⟨0.06, 0.04, 0.04⟩	⟨0.09, 0.02, 0.01⟩	⟨0.08, 0.03, 0.02⟩	⟨0.06, 0.04, 0.04⟩	⟨0.09, 0.02, 0.02⟩	⟨0.09, 0.02, 0.01⟩	⟨0.08, 0.03, 0.02⟩	⟨0.09, 0.02, 0.01⟩
c_4	⟨0.08, 0.03, 0.03⟩	⟨0.08, 0.03, 0.02⟩	⟨0.10, 0.01, 0.01⟩	⟨0.01, 0.09, 0.1⟩	⟨0.05, 0.06, 0.07⟩	⟨0.10, 0.01, 0.01⟩	⟨0.09, 0.02, 0.02⟩	⟨0.08, 0.03, 0.02⟩	⟨0.08, 0.03, 0.03⟩	⟨0.09, 0.02, 0.02⟩	⟨0.09, 0.02, 0.02⟩	⟨0.09, 0.02, 0.02⟩
c_5	⟨0.09, 0.02, 0.01⟩	⟨0.09, 0.02, 0.02⟩	⟨0.10, 0.01, 0.01⟩	⟨0.09, 0.02, 0.01⟩	⟨0.01, 0.09, 0.01⟩	⟨0.09, 0.02, 0.02⟩	⟨0.10, 0.01, 0.01⟩	⟨0.07, 0.04, 0.04⟩	⟨0.09, 0.02, 0.01⟩	⟨0.09, 0.02, 0.02⟩	⟨0.09, 0.02, 0.02⟩	⟨0.09, 0.02, 0.02⟩
c_6	⟨0.08, 0.03, 0.02⟩	⟨0.09, 0.02, 0.02⟩	⟨0.05, 0.05, 0.06⟩	⟨0.07, 0.03, 0.03⟩	⟨0.06, 0.05, 0.05⟩	⟨0.01, 0.09, 0.1⟩	⟨0.07, 0.04, 0.04⟩	⟨0.09, 0.02, 0.02⟩	⟨0.08, 0.05, 0.04⟩	⟨0.09, 0.02, 0.01⟩	⟨0.09, 0.02, 0.02⟩	⟨0.08, 0.03, 0.02⟩
c_7	⟨0.09, 0.03, 0.03⟩	⟨0.08, 0.03, 0.02⟩	⟨0.09, 0.02, 0.02⟩	⟨0.08, 0.03, 0.02⟩	⟨0.09, 0.02, 0.02⟩	⟨0.09, 0.02, 0.02⟩	⟨0.01, 0.09, 0.1⟩	⟨0.08, 0.03, 0.02⟩	⟨0.09, 0.02, 0.01⟩	⟨0.09, 0.02, 0.01⟩	⟨0.09, 0.02, 0.02⟩	⟨0.01, 0.09, 0.1⟩
c_8	⟨0.07, 0.04, 0.04⟩	⟨0.09, 0.02, 0.02⟩	⟨0.08, 0.03, 0.02⟩	⟨0.07, 0.04, 0.04⟩	⟨0.08, 0.03, 0.02⟩	⟨0.09, 0.02, 0.01⟩	⟨0.08, 0.03, 0.02⟩	⟨0.01, 0.09, 0.1⟩	⟨0.09, 0.02, 0.02⟩	⟨0.08, 0.03, 0.02⟩	⟨0.09, 0.02, 0.01⟩	⟨0.09, 0.02, 0.02⟩
c_9	⟨0.09, 0.02, 0.01⟩	⟨0.10, 0.01, 0.01⟩	⟨0.09, 0.02, 0.02⟩	⟨0.06, 0.04, 0.04⟩	⟨0.07, 0.04, 0.04⟩	⟨0.09, 0.02, 0.02⟩	⟨0.09, 0.02, 0.02⟩	⟨0.08, 0.03, 0.02⟩	⟨0.01, 0.09, 0.1⟩	⟨0.09, 0.02, 0.02⟩	⟨0.09, 0.02, 0.02⟩	⟨0.08, 0.03, 0.03⟩
c_{10}	⟨0.09, 0.02, 0.02⟩	⟨0.09, 0.02, 0.01⟩	⟨0.05, 0.05, 0.06⟩	⟨0.07, 0.04, 0.04⟩	⟨0.07, 0.04, 0.04⟩	⟨0.09, 0.02, 0.02⟩	⟨0.09, 0.02, 0.02⟩	⟨0.05, 0.05, 0.06⟩	⟨0.08, 0.03, 0.03⟩	⟨0.01, 0.09, 0.1⟩	⟨0.09, 0.02, 0.02⟩	⟨0.05, 0.05, 0.06⟩
c_{11}	⟨0.07, 0.04, 0.04⟩	⟨0.08, 0.03, 0.03⟩	⟨0.05, 0.06, 0.07⟩	⟨0.03, 0.07, 0.08⟩	⟨0.05, 0.06, 0.07⟩	⟨0.06, 0.04, 0.04⟩	⟨0.07, 0.03, 0.04⟩	⟨0.08, 0.03, 0.02⟩	⟨0.09, 0.02, 0.02⟩	⟨0.09, 0.02, 0.02⟩	⟨0.01, 0.09, 0.1⟩	⟨0.01, 0.09, 0.1⟩
c_{12}	⟨0.05, 0.06, 0.07⟩	⟨0.08, 0.03, 0.03⟩	⟨0.02, 0.08, 0.09⟩	⟨0.02, 0.08, 0.09⟩	⟨0.04, 0.07, 0.08⟩	⟨0.06, 0.04, 0.04⟩	⟨0.06, 0.05, 0.05⟩	⟨0.09, 0.02, 0.02⟩	⟨0.09, 0.02, 0.02⟩	⟨0.10, 0.01, 0.01⟩	⟨0.09, 0.02, 0.01⟩	⟨0.01, 0.09, 0.1⟩

Table 6. The total direct-influence matrix S_c for factors.

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}
c_1	$\langle 0.46, 0.12, 0.13 \rangle$	$\langle 0.59, 0.04, 0.03 \rangle$	$\langle 0.44, 0.06, 0.06 \rangle$	$\langle 0.43, 0.07, 0.07 \rangle$	$\langle 0.40, 0.1, 0.11 \rangle$	$\langle 0.58, 0.03, 0.03 \rangle$	$\langle 0.52, 0.06, 0.06 \rangle$	$\langle 0.46, 0.08, 0.09 \rangle$	$\langle 0.55, 0.07, 0.07 \rangle$	$\langle 0.6, 0.04, 0.04 \rangle$	$\langle 0.6, 0.04, 0.04 \rangle$	$\langle 0.57, 0.04, 0.04 \rangle$
c_2	$\langle 0.51, 0.07, 0.07 \rangle$	$\langle 0.51, 0.11, 0.12 \rangle$	$\langle 0.41, 0.09, 0.11 \rangle$	$\langle 0.42, 0.09, 0.09 \rangle$	$\langle 0.42, 0.08, 0.08 \rangle$	$\langle 0.58, 0.04, 0.03 \rangle$	$\langle 0.53, 0.06, 0.05 \rangle$	$\langle 0.48, 0.08, 0.08 \rangle$	$\langle 0.57, 0.04, 0.04 \rangle$	$\langle 0.6, 0.04, 0.04 \rangle$	$\langle 0.6, 0.04, 0.03 \rangle$	$\langle 0.57, 0.04, 0.04 \rangle$
c_3	$\langle 0.58, 0.04, 0.04 \rangle$	$\langle 0.64, 0.04, 0.03 \rangle$	$\langle 0.42, 0.12, 0.13 \rangle$	$\langle 0.47, 0.07, 0.06 \rangle$	$\langle 0.46, 0.07, 0.07 \rangle$	$\langle 0.63, 0.03, 0.03 \rangle$	$\langle 0.58, 0.05, 0.04 \rangle$	$\langle 0.52, 0.07, 0.06 \rangle$	$\langle 0.62, 0.04, 0.04 \rangle$	$\langle 0.66, 0.03, 0.03 \rangle$	$\langle 0.64, 0.05, 0.04 \rangle$	$\langle 0.62, 0.03, 0.03 \rangle$
c_4	$\langle 0.57, 0.06, 0.05 \rangle$	$\langle 0.64, 0.04, 0.04 \rangle$	$\langle 0.51, 0.04, 0.03 \rangle$	$\langle 0.42, 0.12, 0.13 \rangle$	$\langle 0.45, 0.09, 0.1 \rangle$	$\langle 0.64, 0.03, 0.03 \rangle$	$\langle 0.59, 0.04, 0.03 \rangle$	$\langle 0.54, 0.05, 0.05 \rangle$	$\langle 0.62, 0.04, 0.04 \rangle$	$\langle 0.66, 0.04, 0.03 \rangle$	$\langle 0.66, 0.04, 0.03 \rangle$	$\langle 0.63, 0.04, 0.03 \rangle$
c_5	$\langle 0.62, 0.04, 0.03 \rangle$	$\langle 0.69, 0.04, 0.03 \rangle$	$\langle 0.54, 0.03, 0.03 \rangle$	$\langle 0.53, 0.04, 0.03 \rangle$	$\langle 0.44, 0.12, 0.13 \rangle$	$\langle 0.68, 0.04, .03 \rangle$	$\langle 0.64, 0.03, 0.02 \rangle$	$\langle 0.57, 0.06, 0.06 \rangle$	$\langle 0.67, 0.03, 0.03 \rangle$	$\langle 0.7, 0.04, 0.03 \rangle$	$\langle 0.7, 0.03, 0.03 \rangle$	$\langle 0.67, 0.03, 0.03 \rangle$
c_6	$\langle 0.54, 0.05, 0.05 \rangle$	$\langle 0.61, 0.04, 0.04 \rangle$	$\langle 0.44, 0.08, 0.09 \rangle$	$\langle 0.45, 0.07, 0.06 \rangle$	$\langle 0.43, 0.08, 0.08 \rangle$	$\langle 0.52, 0.11, 0.12 \rangle$	$\langle 0.54, 0.06, 0.06 \rangle$	$\langle 0.51, 0.05, 0.05 \rangle$	$\langle 0.58, 0.05, 0.04 \rangle$	$\langle 0.62, 0.03, 0.03 \rangle$	$\langle 0.62, 0.04, 0.03 \rangle$	$\langle 0.58, 0.05, 0.04 \rangle$
c_7	$\langle 0.61, 0.05, 0.05 \rangle$	$\langle 0.67, 0.05, 0.04 \rangle$	$\langle 0.53, 0.04, 0.04 \rangle$	$\langle 0.51, 0.05, 0.05 \rangle$	$\langle 0.5, 0.05, 0.05 \rangle$	$\langle 0.66, 0.03, 0.03 \rangle$	$\langle 0.55, 0.11, 0.12 \rangle$	$\langle 0.57, 0.05, 0.05 \rangle$	$\langle 0.66, 0.03, 0.03 \rangle$	$\langle 0.69, 0.03, 0.03 \rangle$	$\langle 0.69, 0.03, 0.03 \rangle$	$\langle 0.66, 0.03, 0.03 \rangle$
c_8	$\langle 0.57, 0.06, 0.06 \rangle$	$\langle 0.65, 0.03, 0.03 \rangle$	$\langle 0.5, 0.05, 0.05 \rangle$	$\langle 0.47, 0.07, 0.07 \rangle$	$\langle 0.48, 0.06, 0.05 \rangle$	$\langle 0.64, 0.03, 0.03 \rangle$	$\langle 0.59, 0.05, 0.04 \rangle$	$\langle 0.48, 0.12, 0.13 \rangle$	$\langle 0.63, 0.04, 0.04 \rangle$	$\langle 0.66, 0.04, 0.04 \rangle$	$\langle 0.66, 0.03, 0.03 \rangle$	$\langle 0.63, 0.04, 0.04 \rangle$
c_9	$\langle 0.59, 0.04, 0.03 \rangle$	$\langle 0.66, 0.03, 0.03 \rangle$	$\langle 0.5, 0.05, 0.05 \rangle$	$\langle 0.48, 0.07, 0.07 \rangle$	$\langle 0.47, 0.07, 0.07 \rangle$	$\langle 0.64, 0.04, 0.04 \rangle$	$\langle 0.6, 0.04, 0.04 \rangle$	$\langle 0.55, 0.05, 0.04 \rangle$	$\langle 0.56, 0.11, 0.12 \rangle$	$\langle 0.67, 0.03, 0.03 \rangle$	$\langle 0.66, 0.04, 0.03 \rangle$	$\langle 0.62, 0.04, 0.05 \rangle$
c_{10}	$\langle 0.53, 0.05, 0.05 \rangle$	$\langle 0.59, 0.04, 0.03 \rangle$	$\langle 0.42, 0.09, 0.1 \rangle$	$\langle 0.43, 0.07, 0.07 \rangle$	$\langle 0.42, 0.08, 0.08 \rangle$	$\langle 0.58, 0.04, 0.04 \rangle$	$\langle 0.54, 0.05, 0.05 \rangle$	$\langle 0.46, 0.09, 0.09 \rangle$	$\langle 0.56, 0.05, 0.05 \rangle$	$\langle 0.53, 0.11, 0.12 \rangle$	$\langle 0.59, 0.04, 0.04 \rangle$	$\langle 0.53, 0.08, 0.09 \rangle$
c_{11}	$\langle 0.48, 0.07, 0.07 \rangle$	$\langle 0.55, 0.05, 0.06 \rangle$	$\langle 0.39, 0.09, 0.11 \rangle$	$\langle 0.38, 0.11, 0.12 \rangle$	$\langle 0.38, 0.1, 0.12 \rangle$	$\langle 0.52, 0.07, 0.07 \rangle$	$\langle 0.5, 0.06, 0.07 \rangle$	$\langle 0.47, 0.06, 0.06 \rangle$	$\langle 0.54, 0.04, 0.04 \rangle$	$\langle 0.57, 0.04, 0.04 \rangle$	$\langle 0.49, 0.11, 0.13 \rangle$	$\langle 0.54, 0.04, 0.03 \rangle$
c_{12}	$\langle 0.43, 0.09, 0.1 \rangle$	$\langle 0.52, 0.05, 0.05 \rangle$	$\langle 0.35, 0.12, 0.14 \rangle$	$\langle 0.34, 0.13, 0.14 \rangle$	$\langle 0.35, 0.12, 0.14 \rangle$	$\langle 0.49, 0.07, 0.07 \rangle$	$\langle 0.45, 0.08, 0.08 \rangle$	$\langle 0.44, 0.06, 0.06 \rangle$	$\langle 0.51, 0.05, 0.05 \rangle$	$\langle 0.54, 0.04, 0.03 \rangle$	$\langle 0.53, 0.04, 0.04 \rangle$	$\langle 0.43, 0.12, 0.13 \rangle$

The deneutrosophied total-influence matrix S can be obtained by Equation (3) and illustrated as in Table 7 (for factors) and Table 8 (for dimensions). The a_i and b_i values in Table 9 are obtained from summing the rows and columns of the neutrosophic total relation matrix, respectively. The NRM is constructed by mapping deneutrosophied $(a_i + b_i)$ and values, as indicated in Figures 2–5.

Table 7. The deneutrosophied total-influence matrix S_c for factors.

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}
c_1	0.671	0.763	0.673	0.668	0.643	0.758	0.719	0.681	0.734	0.766	0.765	0.748
c_2	0.713	0.705	0.652	0.657	0.660	0.757	0.726	0.691	0.750	0.768	0.768	0.750
c_3	0.753	0.791	0.653	0.691	0.681	0.786	0.754	0.719	0.778	0.801	0.790	0.781
c_4	0.749	0.791	0.715	0.650	0.670	0.792	0.763	0.732	0.780	0.802	0.800	0.782
c_5	0.782	0.819	0.735	0.727	0.662	0.812	0.792	0.745	0.810	0.827	0.825	0.807
c_6	0.731	0.772	0.669	0.677	0.664	0.709	0.728	0.716	0.755	0.781	0.776	0.756
c_7	0.770	0.807	0.724	0.712	0.709	0.804	0.722	0.746	0.802	0.822	0.817	0.801
c_8	0.744	0.799	0.706	0.692	0.696	0.791	0.758	0.682	0.783	0.799	0.803	0.781
c_9	0.763	0.803	0.711	0.692	0.689	0.790	0.765	0.736	0.730	0.806	0.802	0.780
c_{10}	0.725	0.762	0.657	0.666	0.660	0.753	0.730	0.680	0.742	0.710	0.763	0.722
c_{11}	0.695	0.734	0.641	0.628	0.631	0.718	0.705	0.687	0.732	0.748	0.690	0.733
c_{12}	0.663	0.719	0.609	0.604	0.611	0.700	0.678	0.676	0.713	0.732	0.729	0.657

Table 8. The deneutrosophied total influence matrix S_D for dimensions.

	D_1	D_2	D_3
D_1	0.30	0.36	0.35
D_2	0.33	0.26	0.36
D_3	0.37	0.38	0.29

The a_i and b_i values in Table 9 are obtained from summing the rows and columns of the neutrosophic total relation matrix, respectively.

Table 9. The sum of causes and effects on dimensions and factors.

Dimensions/Factors	a_i	b_i	a_i+b_i	a_i−b_i
Natural factors (D_1)	2.37	2.47	4.84	−0.10
Wave and current (c_1)	8.59	8.76	17.35	−0.17
Sediment transport (c_2)	8.60	9.27	17.86	−0.67
Storm surge (c_3)	8.98	8.15	17.12	0.83
Tidal range (c_4)	9.03	8.06	17.09	0.96
Global warming (c_5)	9.34	7.98	17.32	1.37
Beach profile and stability (c_6)	8.74	9.17	17.91	−0.44
Sea level rise (c_7)	9.24	8.84	18.07	0.40
Man-made factors (D_2)	2.52	2.38	4.89	0.14
Sand mining activities (c_8)	9.03	8.49	17.53	0.54
Coastal development (c_9)	9.07	9.11	18.18	−0.04
Socio-economic factors (D_3)	2.51	2.55	5.06	−0.04
Coastal protection (c_{10})	8.57	9.36	17.93	−0.79
Budgetary revenue (c_{11})	8.34	9.33	17.67	−0.98
Coastal zone management (c_{12})	8.09	9.10	17.19	−1.01

The NRM is constructed by mapping deneutrosophied $(a_i + b_i)$ and $(a_i - b_i)$ values. Figure 2 shows the coordinates of the dimensions where D_1 is influenced by D_2 and D_3. The threshold value is set at 0.33, which will produce the NRM among the dimensions, as shown in Figure 2.

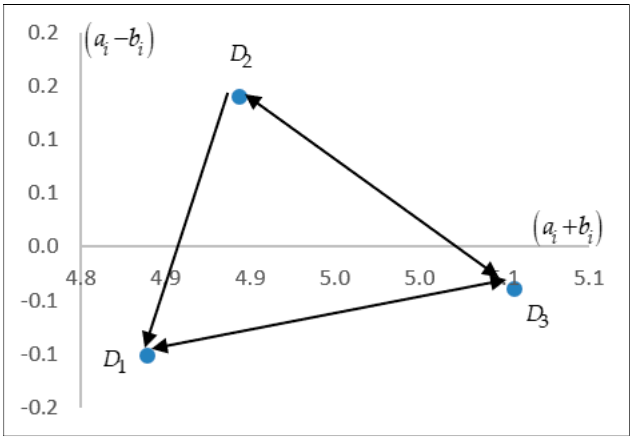

Figure 2. The network relationship map (NRM) within dimensions of coastal erosion.

The threshold value for factors is set at 0.730. Thus, the coordinates and causal direction of the natural factors are presented after eliminating the minor effects and causes that were lower than the threshold value. Figure 3 shows the NRM of factors within dimension D_1.

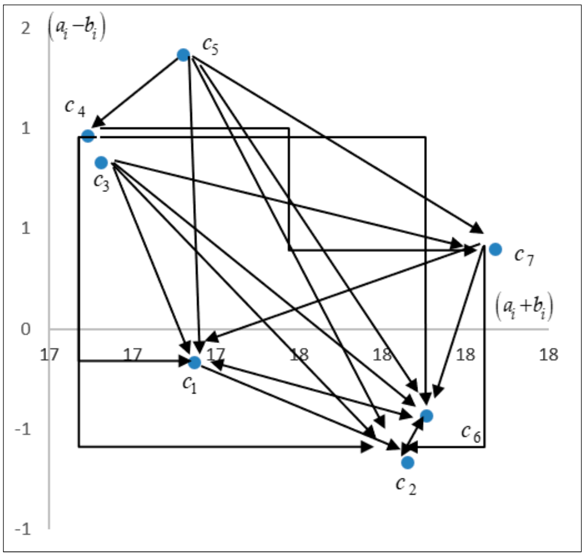

Figure 3. The NRM within factors of natural factors (D_1) of coastal erosion.

For man-made factors of D_2 coastal erosion, the NRM is shown in Figure 4.

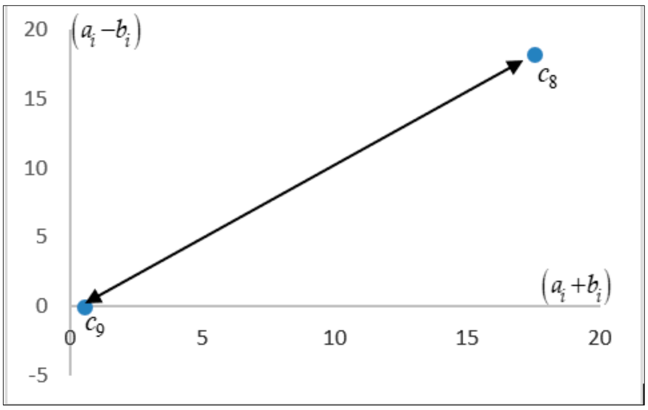

Figure 4. The NRM within factors of man-made factors (D_2) of coastal erosion.

Under the socio-economic dimension, the factors are mapped in the negative quadrant of the $(a_i - b_i)$ axis. The coordinates of the three factors are shown in Figure 5.

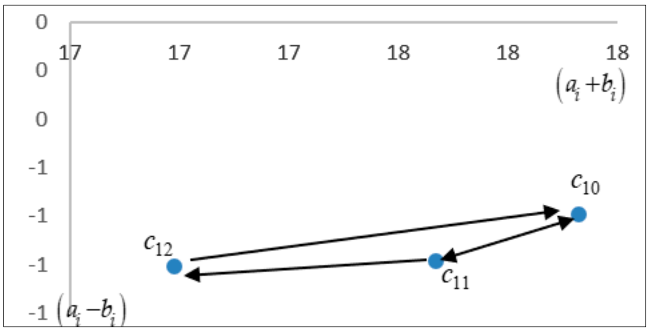

Figure 5. The NRM within factors of socio-economic factors (D_3) of coastal erosion.

The network relationship mapping obtained via the proposed method can provide a better understanding of the entire structure. Then, the neutrosophic total-influence matrix, S, is normalized using Equation (13), and it is shown in Table 10.

Table 10. The new matrix S_c^{α}.

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}
c_1	0.137	0.156	0.138	0.137	0.131	0.155	0.147	0.481	0.519	0.336	0.336	0.328
c_2	0.146	0.145	0.134	0.135	0.135	0.155	0.149	0.479	0.521	0.336	0.336	0.328
c_3	0.147	0.155	0.128	0.135	0.133	0.154	0.148	0.480	0.520	0.338	0.333	0.329
c_4	0.146	0.154	0.139	0.127	0.131	0.154	0.149	0.484	0.516	0.336	0.335	0.328
c_5	0.147	0.154	0.138	0.136	0.124	0.152	0.149	0.479	0.521	0.336	0.336	0.328
c_6	0.148	0.156	0.135	0.137	0.134	0.143	0.147	0.487	0.513	0.338	0.335	0.327
c_7	0.147	0.154	0.138	0.136	0.135	0.153	0.137	0.482	0.518	0.337	0.335	0.328
c_8	0.143	0.154	0.136	0.133	0.134	0.153	0.146	0.466	0.534	0.335	0.337	0.328
c_9	0.146	0.154	0.136	0.133	0.132	0.152	0.147	0.502	0.498	0.337	0.336	0.327
c_{10}	0.146	0.154	0.133	0.134	0.133	0.152	0.147	0.478	0.522	0.323	0.348	0.329
c_{11}	0.146	0.154	0.135	0.132	0.133	0.151	0.148	0.484	0.516	0.344	0.318	0.338
c_{12}	0.145	0.157	0.133	0.132	0.133	0.153	0.148	0.486	0.514	0.346	0.344	0.310

The next step is to construct the transpose matrix. By transposing the normalized neutrosophic total-influence matrix S^{α}, the unweighted supermatrix ψ is obtained. Table 11 shows the unweighted supermatrix.

Table 11. The unweighted supermatrix, ψ.

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}
c_1	0.137	0.146	0.147	0.146	0.147	0.148	0.147	0.143	0.146	0.146	0.146	0.145
c_2	0.156	0.145	0.155	0.154	0.154	0.156	0.154	0.154	0.154	0.154	0.154	0.157
c_3	0.138	0.134	0.128	0.139	0.138	0.135	0.138	0.136	0.136	0.133	0.135	0.133
c_4	0.137	0.135	0.135	0.127	0.136	0.137	0.136	0.133	0.133	0.134	0.132	0.132
c_5	0.131	0.135	0.133	0.131	0.124	0.134	0.135	0.134	0.132	0.133	0.133	0.133
c_6	0.155	0.155	0.154	0.154	0.152	0.143	0.153	0.153	0.152	0.152	0.151	0.153
c_7	0.147	0.149	0.148	0.149	0.149	0.147	0.137	0.146	0.147	0.147	0.148	0.148
c_8	0.481	0.479	0.480	0.484	0.479	0.487	0.482	0.466	0.502	0.478	0.484	0.486
c_9	0.519	0.521	0.520	0.516	0.521	0.513	0.518	0.534	0.498	0.522	0.516	0.514
c_{10}	0.336	0.336	0.338	0.336	0.336	0.338	0.337	0.335	0.337	0.323	0.344	0.346
c_{11}	0.336	0.336	0.333	0.335	0.336	0.335	0.335	0.337	0.336	0.348	0.318	0.344
c_{12}	0.328	0.328	0.329	0.328	0.328	0.327	0.328	0.328	0.327	0.329	0.338	0.310

Table 12 shows the unweighted matrix of DMs.

Table 12. The new matrix S_D^{α}.

	D_1	D_2	D_3
D_1	0.29	0.36	0.35
D_2	0.35	0.27	0.38
D_3	0.36	0.36	0.28

By multiplying the elements in the unweighted supermatrix ψ of factors (Table 11) and the new matrix of dimensions, S_D^{α} (Table 12), the weighted supermatrix, ψ^{α} in Table 13 is constructed.

Table 13. The weighted supermatrix ψ^{α} of dimensions.

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}
c_1	0.041	0.044	0.044	0.044	0.044	0.044	0.044	0.052	0.053	0.051	0.051	0.051
c_2	0.047	0.043	0.046	0.046	0.046	0.047	0.046	0.055	0.055	0.054	0.054	0.055
c_3	0.041	0.040	0.038	0.042	0.041	0.041	0.041	0.049	0.049	0.046	0.047	0.046
c_4	0.041	0.040	0.041	0.038	0.041	0.041	0.041	0.048	0.048	0.047	0.046	0.046
c_5	0.039	0.041	0.040	0.039	0.037	0.040	0.041	0.048	0.048	0.047	0.046	0.047
c_6	0.046	0.047	0.046	0.046	0.046	0.043	0.046	0.055	0.055	0.053	0.053	0.053
c_7	0.044	0.045	0.044	0.045	0.045	0.044	0.041	0.053	0.053	0.052	0.052	0.052
c_8	0.159	0.158	0.158	0.160	0.158	0.161	0.159	0.121	0.131	0.172	0.174	0.175
c_9	0.171	0.172	0.172	0.170	0.172	0.169	0.171	0.139	0.129	0.188	0.186	0.185
c_{10}	0.124	0.124	0.125	0.124	0.124	0.125	0.125	0.127	0.128	0.094	0.100	0.100
c_{11}	0.124	0.124	0.123	0.124	0.124	0.124	0.124	0.128	0.128	0.101	0.092	0.100
c_{12}	0.121	0.121	0.122	0.121	0.121	0.121	0.121	0.125	0.124	0.095	0.098	0.090

Table 14 shows the limited supermatrix by limiting the power of the weighted supermatrix.

Table 14. The limiting supermatrix.

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}
c_1	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049
c_2	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052
c_3	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
c_4	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
c_5	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
c_6	0.051	0.051	0.051	0.051	0.051	0.051	0.051	0.051	0.051	0.051	0.051	0.051
c_7	0.050	0.049	0.049	0.049	0.049	0.050	0.050	0.050	0.050	0.050	0.049	0.050
c_8	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153
c_9	0.164	0.164	0.164	0.164	0.164	0.164	0.164	0.164	0.164	0.164	0.164	0.164
c_{10}	0.116	0.116	0.116	0.116	0.116	0.116	0.116	0.116	0.116	0.116	0.116	0.116
c_{11}	0.116	0.116	0.116	0.116	0.116	0.116	0.116	0.116	0.116	0.116	0.116	0.116
c_{12}	0.113	0.113	0.113	0.113	0.113	0.113	0.113	0.113	0.113	0.113	0.113	0.113

Finally, the rows in the limited supermatrix contribute the weight of the factor of coastal erosion. The overall local weights and global weights of factors and dimensions are illustrated in Table 15.

The results show that coastal development (C_9) is the most important factor, with a weight of 0.164, followed by sand mining activities (C_8) at 0.153 and coastal protection (C_{10}) and budgetary revenue (C_{11}), which are both at 0.116. Relative to other factors, the DM suggests that the storm surge (C_3), tidal range (C_4), and global warming (C_5) are the least important factors with the global weights of 0.045. With respect to each dimension, the DMs indicate that sediment transport (C_2) is the most important factor in the dimension of natural factors (D_1), while coastal development (C_9) is the most important of the man-made factors (D_2). It also concludes that coastal protection (C_{10}) and budgetary revenue (C_{11}) are the most important factors under socio-economic factors (D_3).

Table 15. The weights of dimensions and factors of coastal erosion.

Dimensions/Factors	Local Weights	Global Weights
Natural factors	0.336	
Wave and current (c_1)	0.145	0.049
Sediment transport (c_2)	0.153	0.052
Storm surge (c_3)	0.136	0.045
Tidal range (c_4)	0.135	0.045
Global warming (c_5)	0.132	0.045
Beach profile and stability (c_6)	0.152	0.051
Sea level rise (c_7)	0.146	0.05
Man-made factors	0.317	
Sand mining activities (c_8)	0.484	0.153
Coastal development (c_9)	0.516	0.164
Socio-economic factors	0.347	
Coastal protection (c_{10})	0.338	0.116
Budgetary revenue (c_{11})	0.337	0.116
Coastal zone management (c_{12})	0.326	0.113

4.5. Discussion and Implications

Based on the results, we know that the degrees of influence of coastal erosion factors are different from each other. The traditional average method, which assumes that the weights of clusters are equal, is thus irrational. Therefore, the normalized total-influence matrix S_c of DEMATEL is incorporated into the ANP method, which is able to consider the influential weight of each cluster. The findings show that the coastal development with the weightage of 0.164 is the most important factor for coastal erosion. Consequently, this study clearly shows the influence of the man-made factors on coastal erosion. Man-made factors such as coastal development are one of the factors that influenced the coastal environment and triggered the destruction of the natural dynamic ecosystem and coastline changes. Human influence on coastal environment and erosion can be connected to the demands and effects of coastal development. The development along coastal areas includes the engineering works such as land reclamation for urban expansion and airport extension, the dredging of navigational channels, and the construction of ports, harbors, groynes, breakwaters, and jetties. These developments can cause the interruption of long-shore sediment supply, which can cause either coastal erosion or accretion. Therefore, the government or stakeholders should pay more attention to the development projects near the coastal zone areas.

In addition, the problems of coastal erosion can be improved based on the NRM in Figures 2–5, which were obtained via the DEMATEL method to comprehensively understand the interrelationships between dimensions and factors. Through the NRM, $(a_i + b_i)$ indicates the degree of influences given and received, and it shows the importance index that each dimension and factor contributed to the problem. On the other hand, $(a_i - b_i)$ categorizes the factors into net causer and net receiver groups. If the $(a_i - b_i)$ value is positive, it indicates that the particular factor is influenced by the other factors, and if $(a_i - b_i)$ is negative, then it means that the factor is being influenced by other factors. Considering the $(a_i + b_i)$ and $(a_i - b_i)$ values in Figure 2, it seems that the man-made factor should first be improved, because it influences the other dimensions the most. That is, if stakeholders plan the man-made factor well, it will improve the other two dimensions. They also can begin on the coastal development factor and sand-mining activities to improve the man-made factors dimension. As seen in Figure 2, it also determines that the natural factors dimension is being influenced the most, followed by the socio-economic factors dimension.

Collectively, this study of combining neutrosophic DEMATEL and ANP methods provides a comprehensive yet simple decision-making model, which can help solve complicated decision problems. This study outlines a critical role for finding the importance of each dimension and provides important insights on how to improve the coastal erosion problems.

5. Comparative Analysis

The comparative analysis is also made to compare the degree of importance of criteria obtained using the proposed method with the DEMATEL, fuzzy DEMATEL, and neutrosophic DEMATEL methods. Table 16 shows a comparative analysis of the proposed NS-DANP method with the DEMATEL, fuzzy DEMATEL, and neutrosophic DEMATEL methods, and the respective type of number used.

Table 16. The results of coastal erosion study using different methods.

Evaluation Method	Degree of Importance	Type of Number Used
DEMATEL	$c_9 > c_{10} > c_7 > c_2 > c_6 > c_{11} > c_8 > c_1 > c_3 > c_{12} > c_5 > c_4$	Real number
Fuzzy DEMATEL	$c_9 > c_7 > c_{10} > c_2 > c_6 > c_{11} > c_8 > c_1 > c_3 > c_5 > c_{12} > c_4$	Triangular fuzzy number
Neutrosophic DEMATEL	$c_9 > c_7 > c_{10} > c_6 > c_2 > c_{11} > c_8 > c_1 > c_5 > c_{12} > c_3 > c_4$	Single Valued Neutrosophic Number
NS-DANP	$c_9 > c_7 > c_{10} > c_6 > c_2 > c_{11} > c_8 > c_1 > c_5 > c_{12} > c_3 > c_4$	Single Valued Neutrosophic Number

Based on the Table 16, the degree of importance of factors obtained using the DEMATEL method, fuzzy DEMATEL method, neutrosophic DEMATEL method, and our proposed NS-DANP method are almost consistent. It also can be seen that the results of the neutrosophic DEMATEL method and our proposed NS-DANP method are exactly the same. However, the DEMATEL method only produces the end result of the degree of importance, while our proposed integrated ANP method with DEMATEL can give us the weights of every influential factor. In addition to that, ANP can consider the interaction and dependencies that exist among factors and dimensions. The introduction of the SVNWA aggregation operator in the process of combining all the DMs' judgments can be considered better than just the normal averaging operator. Another distinct feature of the proposed method is the application of SVNSs into the proposed method, which makes it superior to the real number and triangular fuzzy numbers. The SVNS has an edge in dealing with a problem that is characterized by not only uncertainty but also truth, indeterminacy, and falsity information.

6. Conclusions

In this paper, an integrated ANP and DEMATEL method under the neutrosophic environment has been successfully developed. The neutrosophic DEMATEL-based ANP (NS-DANP) method offers two main contributions. Firstly, the single-valued neutrosophic numbers (SVNNs) are used instead of crisps or triangular fuzzy numbers (TFNs) to cater to the indeterminacy elements in the decision-making problem. The linguistic evaluation scale from Biswas et al. [65] was employed to obtain a comprehensive judgment. Secondly, we used the single-valued neutrosophic weighted averaging (SVNWA) aggregation operator proposed by Ye [66] to aggregate all the DMs' judgments. This aggregation operator is simple but powerful enough to aggregate the SVNSs without losing the information.

A case study of the coastal erosion along Peninsular Malaysia coastline areas with 12 factors was implemented using the proposed NS-DANP method to get the most important factor. The results reveal that coastal development is the most important factor, followed by sand mining activities, coastal protection, and budgetary revenue. The stakeholders should pay extra attention to these three factors to minimize the coastal erosion events. The proposed method also successfully classified the factors of coastal erosion into two groups. The factors that caused the coastal erosion problem are sea level rise, tidal range, storm surge, global warming, and sand-mining activities. The other group of factors is known as the effects group, which includes sediment transport, waves and currents, coastal development, beach profile and stability, coastal protection, budgetary revenue, and coastal zone management.

A comparative analysis on the ranking of coastal erosion factors between the proposed NS-DANP method and the other existing methods was done. The results show that the proposed NS-DANP method is consistent with the neutrosophic DEMATEL method and almost consistent with the other two methods. Thus, we can conclude that the proposed NS-DANP is comparable with the other methods. Overall, the proposed NS-DANP method highlights the criteria weight and development of the causal diagram by applying single-valued neutrosophic numbers and the concept of the SVNWA aggregation operator. Besides that, the flaws in computing the multiplicative inverse of fuzzy matrices can be avoided, as SVNNs were used. Nonetheless, this study has some limitations. The relationships between the ideal number of DMs and reliability of the output have been a big question mark in the decision-making field. However, there are several mathematical methods that could be used in validating the reliability of the results. One of them is the sensitivity analysis, which can be incorporated in the future. The analysis could be used to check the sensitivity of the findings in the NRM due to a variety of uncertainty sources in linguistic evaluation.

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